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SEEPAGE FORCES IN A GRAVITY DAM BY ELECTRICAL ANALOGY

by Horace A. Johnson, M. ASCE

SOIL MECHANICS AND FOUNDATIONS DIVISION

{Discussion open until November 1, 1955}

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SEEPAGE FORCES IN A GRAVITY DAM BY ELECTRICAL ANALOGY

Horace A. Johnson,[1] M. ASCE

SYNOPSIS

The purpose of this paper is to present the results of an investigation of seepage forces in a concrete gravity dam and its foundation by means of the electrical analogy. Flow is assumed to occur through both the concrete and the rock foundation, which is contrary to the usual assumption of no flow in concrete or rock. No attempt is made to determine on what percentage of the area the seepage forces may act. A series of electrical analogy models was constructed to show the effects of the various measures taken to prevent uplift in a concrete gravity dam and its foundation, such as grouting and drainage, on seepage forces. The effects of open joints and different ratios of permeability of concrete to the foundation were also investigated. Both two and three dimensional models were constructed.

INTRODUCTION

This paper presents the results of certain electrical analogy tests made on models of a concrete gravity dam and its foundation assuming that both the concrete and foundation are homogeneous, isotropic materials, but with not necessarily the same permeabilities. While these assumptions may appear to be far from the actual conditions, it is believed that the results, as will be shown, do agree well with the actual measurements made on existing dams, and do show the relative effects of certain measures.

The dam cross section adopted for testing has a 0.1 upstream batter and a 0.7 downstream batter. Where a grout curtain was assumed, it was taken as 1/3 the height of the dam, and the depth of foundation drainage holes was assumed to be 1/4 the height of the dam. Drainage holes in the concrete section, where used, were modeled on 10' c.c. Where a height of dam was necessary for scale, 300' was used.

TESTS ON TWO-DIMENSIONAL MODEL

It is not proposed to go into the theory of the electrical analogy since this has been propounded before,[2,3,4,5] or a detailed description of the electrical analogy apparatus or models. A general description of the construction of the models will be given.

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1. Chief, Construction-Operations Div., Sacramento Dist., U.S. Corps of Engineers, Sacramento, Calif.
2. "Motion of Water Under Dams" by N.N. Pavlovsky, Transactions, 1st Cong. on Large Dams, Stockholm, Sweden, 1933, Vol. 4, pp. 179-192.

A two-dimensional model with height H was constructed as shown in Figure 1, plan view, and Figure 2, cross sectional view. The model was

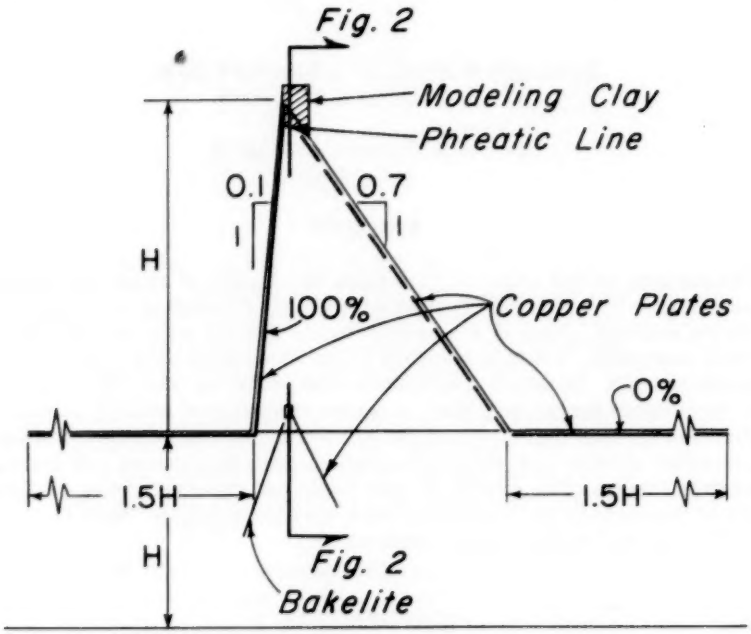

Fig. 1

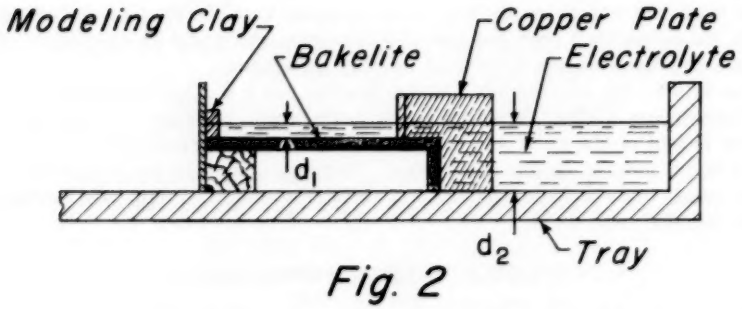

Fig. 2

3. "The Flow Net and the Electrical Analogy" by E.W. Lane, F.B. Campbell, and W.H. Price, Civil Engineering, October 1934, pp. 510-514.
4. "Electrical Analogy Applied to Three Dimensional Study of Percolation Under Dams Built on Pervious Heterogeneous Dams" by B.F. Reltov, Transactions, 2d Cong. on Large Dams, Washington, D.C., Vol. V, 1936, pp. 73-85.
5. "Dams on Porous Media" by Mohamed Ahmed Selim, Trans, ASCE, Vol. 112, 1947, p. 488.

primarily of Bakelite with copper sheets introduced on the inside of the Bakelite wherever it was necessary to impress a potential.

100 per cent potential was impressed on the upstream face of the dam model and for a distance of 1.5 H upstream from the model on the model dam foundation. 0 per cent potential was impressed on the foundation downstream from the dam for a distance of approximately 1.5 H for no tailwater condition, as shown in Figure 1. For tailwater equal to .25 H, 25 per cent potential was impressed on the foundation downstream and to a point .25 H above the foundation on the downstream side of the dam. No drains were modeled in the concrete. The foundation drain was represented by a solid copper sheet connected to the copper gallery. This represents a continuous drain curtain, instead of the usual actual intermittent drains at 10' c.c. This foundation drain was set at 7 per cent potential to correspond to the gallery elevation. Potentials were impressed on the downstream face in increments of 10 per cent from 10 per cent to 90 per cent at the required elevations to force the equipotential lines to intersect the downstream face at the proper points. The foundation was represented for a depth H below the bottom of the dam. This is considered sufficient depth to make the boundary effects negligible. The phreatic line was introduced by using modeling clay and established by trial and error.

The equipotential lines established in the model represent the percentage of height, H, above 0 per cent potential level, to which water would rise in a piezometer introduced at that point. To get the pressure at any point above the 0 per cent potential level, it is thus necessary to subtract the height of the point, in percentage of H, from the potential.

Tests were run for 58 different conditions in the two-dimensional model as shown in Table 1. This sounds like a very large number of tests to run. However, it should be pointed out that after the model was constructed it was only necessary to change the water level, or remove or adjust certain parts of the model so that tests could be very quickly run. The rate of testing was also greatly speeded by a special electronic hookup between the probe and the plotting point on the pantrograph. This was arranged so that when the probe reached a balance point in the model a high voltage spark would be discharged from the pantograph tracing point to an aluminum ground plate under the paper. This burned a small hole in the paper and automatically marked the point. The operator thus had to listen for only the small noise of the spark to know that the point was plotted and move the probe on.

Certain results have been abstracted from tests listed in Table 1 and are shown in Figures 3 to 6. It is believed that these figures show the main points learned from the two dimensional model.

It should be pointed out here that no drainage holes were provided in the concrete section in the two dimensional model. The only drains provided were the foundation drain and the drainage gallery. The effect of drainage in the concrete was later analyzed in the three-dimensional model.

Figure 3 shows the results from Model A-1, where the ratio of concrete permeability to foundation permeability is 1:10, the grout cutoff is impervious, and the drain is 100 per cent effective and is set at 7 per cent potential to correspond to the height of outlet, and there is no tailwater. This permeability ratio is considered a reasonable assumption and the other assumptions are the maximum efficiency. It will be noted that the reduction in potential is very great at the foundation with the maximum equipotential line on the base downstream from the cutoff being about 15 per cent.

A study of the potentials in the dam section at elevations .3 H and .5 H above the base shows that the effect of the foundation treatment on these

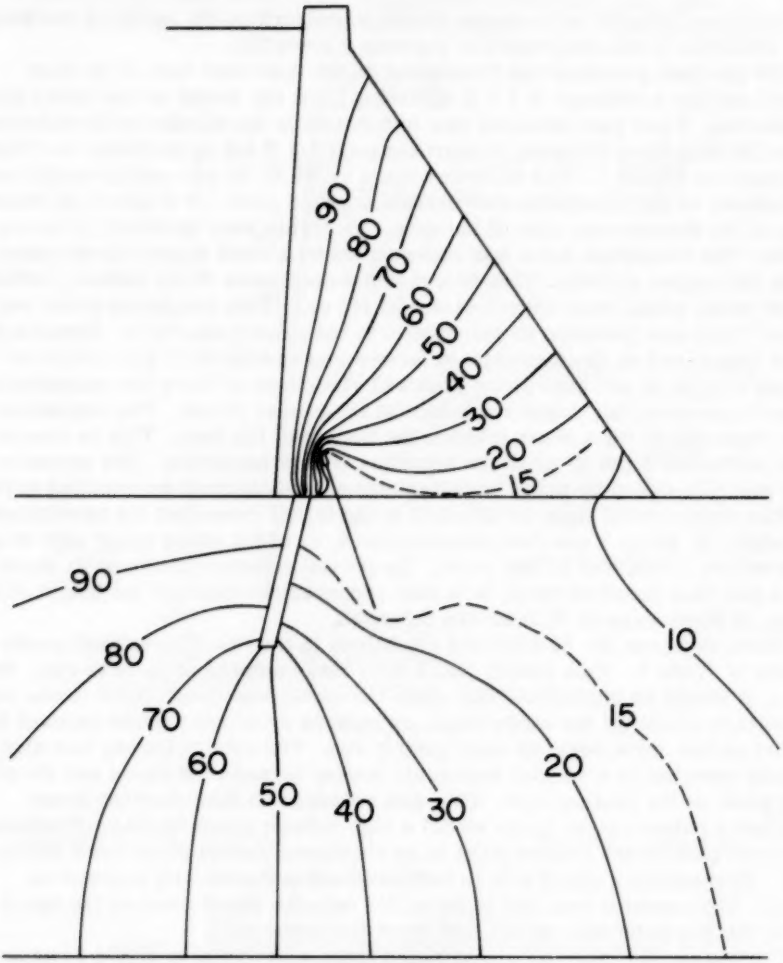

Fig. 3

potentials is small. At the .3 H elevation, for example, the uplift at midsection is 38 per cent compared to the 50 per cent which it would be if there were flow through the concrete only. At .5 H the corresponding figures are 45 per cent and 50 per cent. Test L-1 which was performed under the same conditions except with a permeability ratio of 1:2 shows about the same effect in the concrete.

In Figure 4 is shown the result of Test A-4, which is Test A-1 with the drain removed. It will be noted that the maximum potential downstream from the cutoff has increased to about 60 per cent. Also the potentials in the concrete at .3 H now show no reduction.

Figures 5 and 6 show the effect of different ratios of permeability of the concrete (k_c) to the permeability of the foundation (k_f), for two foundation treatments. Three permeability ratios were tested: 1:2; 1:10; and 1:00.

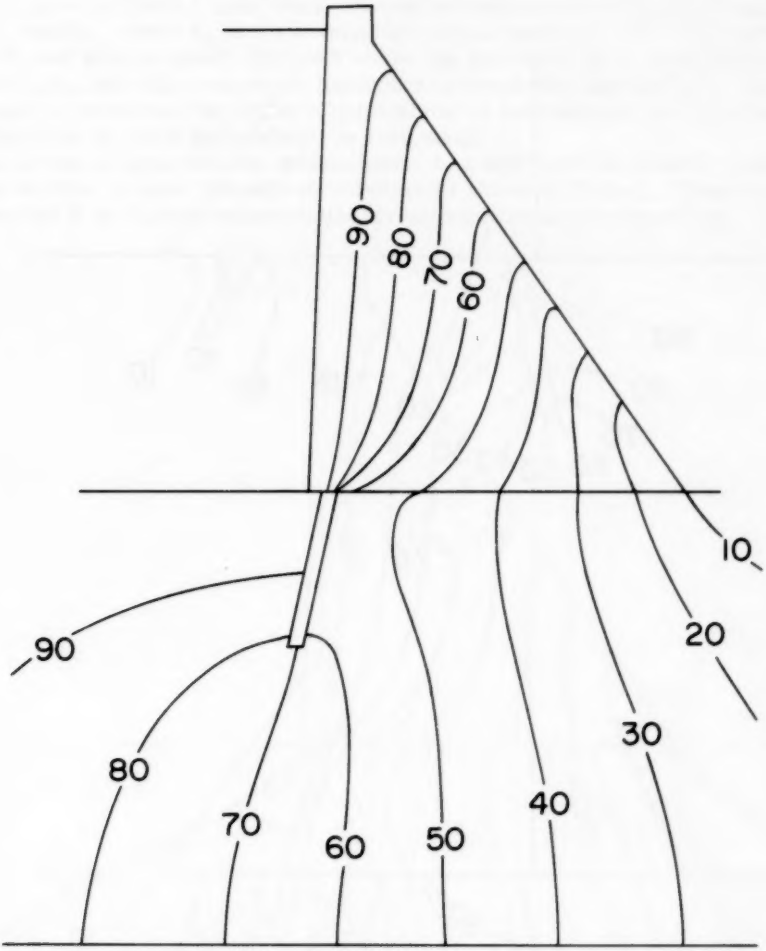

Fig. 4

In other words, on a permeable foundation, the concrete would be respectively: one-half as permeable as the foundation; 1/10 as permeable; and impermeable. Effect of the ratios was obtained in the model by making the depth (d_1) of the electrolyte over the concrete area respectively: one-half the depth (d_2) over the foundation area; 1/10 the depth over the foundation area; and zero. Equipotentials are shown in the foundation only since as shown above the effect on the equipotentials in the concrete is very small. Potential lines are plotted for the permeabilities other than 1:00 only when significantly different from those for 1:00. Comparisons were also plotted for a drain only in the foundation and for no foundation treatment. The equipotential lines were so close together for these conditions, for the three ratios, that they cannot be separated on the small scale drawings except near the downstream edge.

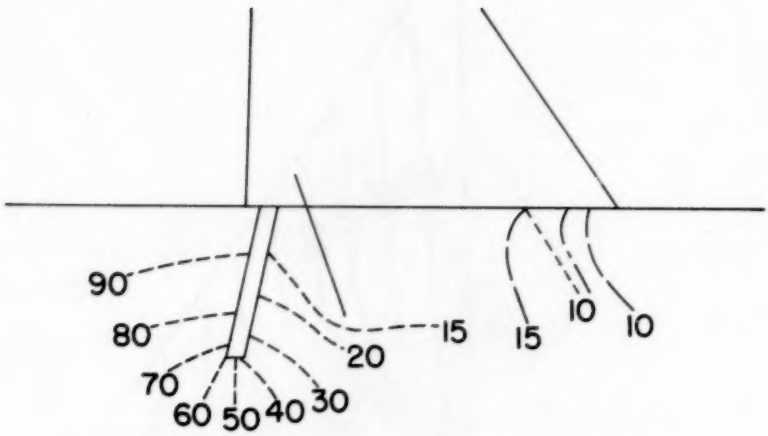

Fig. 5

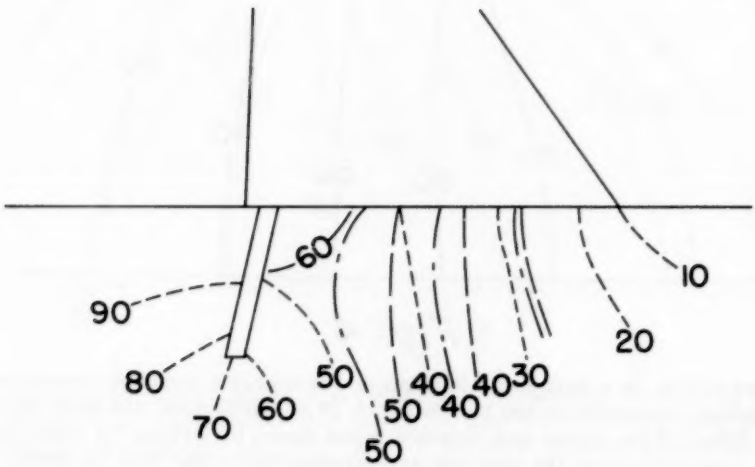

Fig. 6

Permeability 1:00 -------

" 1:10 — - — -

" 1:2 — — —

As noted in Table 1 tests were run with permeabilities of the cutoff equal to k_c and $5k_c$, where k_c is the permeability of the concrete, with impervious cutoff, and with no cutoff. Figure 7 shows the results of these tests with a cutoff only, and with concrete to foundation permeability ratio of 1:10. Where a drain is introduced the effect of the drain is so predominant that the effect of variation of cutoff permeability is very small.

A series of tests was run with tailwater to a depth of 0.25 H under conditions similar to tests run with no tailwater as shown in Table 1. These tests show that if the foundation potentials for no tailwater are increased by

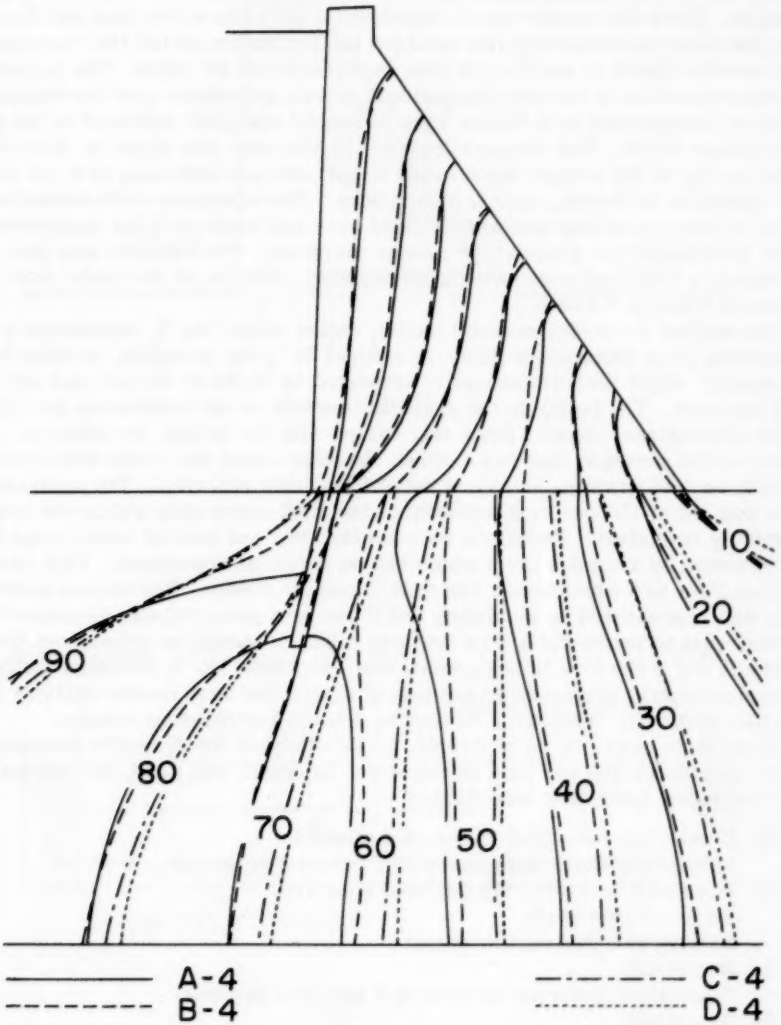

Fig. 7

$\frac{x}{b}$ .25 per cent, where x is the distance from the upstream edge of the dam and b is the base width of the dam, that the resulting potentials will be slightly higher than the actual potentials obtained.

Discussion of the two-dimensional tests will be made and conclusions drawn after description of the results of the three-dimensional tests.

Three Dimensional Tests

Two three-dimensional models were constructed. The first model, called Model No. 2, was constructed as for the two-dimensional model with slight changes. Since this model was to represent a 10' slice of the dam and foundation, the same permeability was used for the foundation as for the concrete. The constant depth of electrolyte thus represents the 10' slice. The gallery is represented as in the two-dimensional model, and where used the foundation drain is represented by a copper wire of proper diameter soldered to the gallery copper block. The vertical drain in the concrete was made by stretching a fine string at the proper depth in the electrolyte and attaching to it, at 10 per cent potential intervals, spirals of fine wire. These spirals were connected to the proper potentials and were shifted back and forth until the equipotential lines intersected the drain at the proper elevation. The phreatic line was introduced by trial and error with modeling clay. Details of the model are shown in Figures 8 and 9.

The second three-dimensional model, called Model No. 3, represents a horizontal slice through the dam. A width of 50', one monolith, is taken for the model. Eight inch drains are represented by wires at 10' c.c. and are set at 0 per cent. The length to the phreatic line was as determined by the first three-dimensional model. Since this varies with the height, the effect of changing the phreatic line was studied. In some cases the joints were considered to be free draining and were set at 0 per cent potential. The upstream face was set at 100 per cent potential to the first water stop which was represented by insulation. The space between the first and second water stops was represented by a copper strip which had no potential impressed. This represents a joint into which water can flow in and out freely. The second water stop was represented by insulation and 0 per cent potential was impressed downstream to represent a free draining joint. It should be pointed out that in Model No. 3 the flow is horizontal, whereas Model No. 2 indicates the flow is approximately horizontal to the line of drains and very nearly vertical past the line of drains. This must be kept in mind in interpreting results.

Four tests were run on Model No. 2. In all cases the drains in the concrete were considered 100 per cent effective and tailwater was zero, and the following foundation conditions were tested.

2a. Foundation cut-off—100 per cent effective
Foundation drain and gallery at 7 per cent potential

2b. Foundation cut-off—100 per cent effective
No foundation drain
Gallery at 7 per cent potential

2c. No cut-off
Foundation drain and gallery at 7 per cent potential

2d. No cut-off
No foundation drain

Figure 10 shows the results of test 2a and Figure 11 shows the results of test 2d. The other results are intermediate between these two.

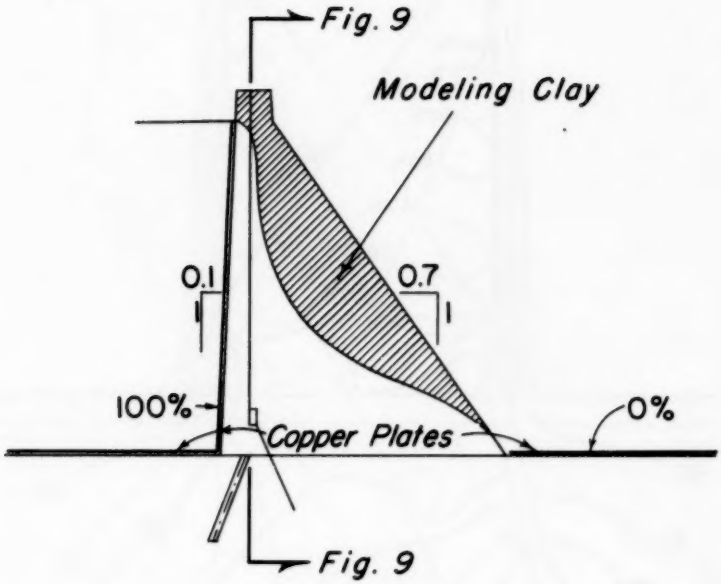
Fig. 9
Modeling Clay
0.1
1
0.7
1
100%
Copper Plates
0%
Fig. 9

Fig. 8

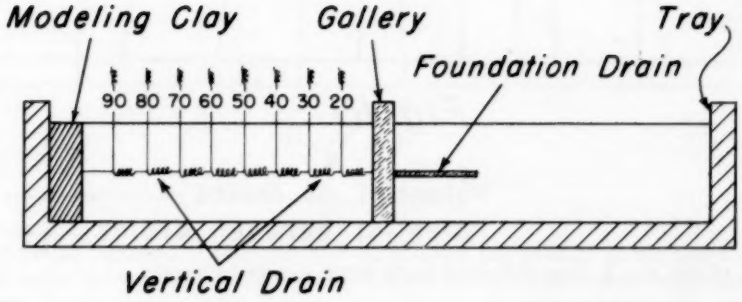
Modeling Clay
Gallery
Tray
Foundation Drain
90 80 70 60 50 40 30 20
Vertical Drain

Fig. 9

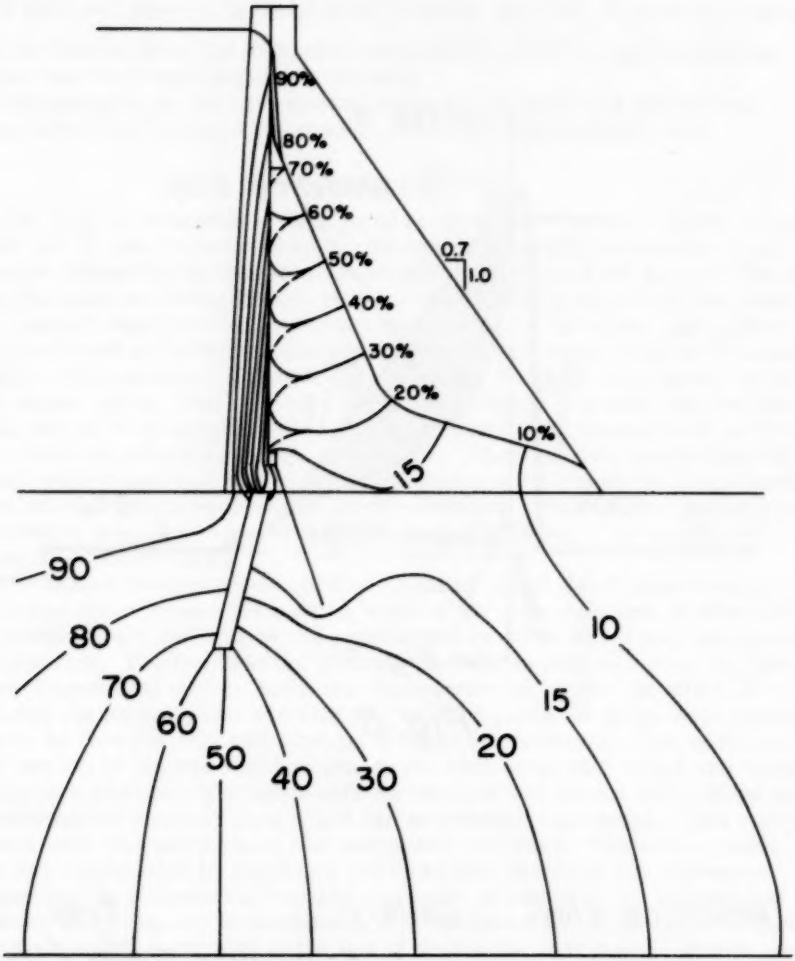

Fig. 10

Potential at drains ————

Potential between drains - - - -

On Model No. 3, five different tests were run as follows:

3a. Drains 100 per cent effective, joints draining; two waterstops
3b. Same as 3a, except 4' diameter cylinder around drain has $k = 0.1k_c$
3c. Joints freely draining; two waterstops
3d. Drains 100 per cent effective; joints not draining
3e. Same as 3d, except 4' diameter cylinder around drains has $k = 0.1k_c$

Figures 12 to 16 respectively indicate the results of these tests.

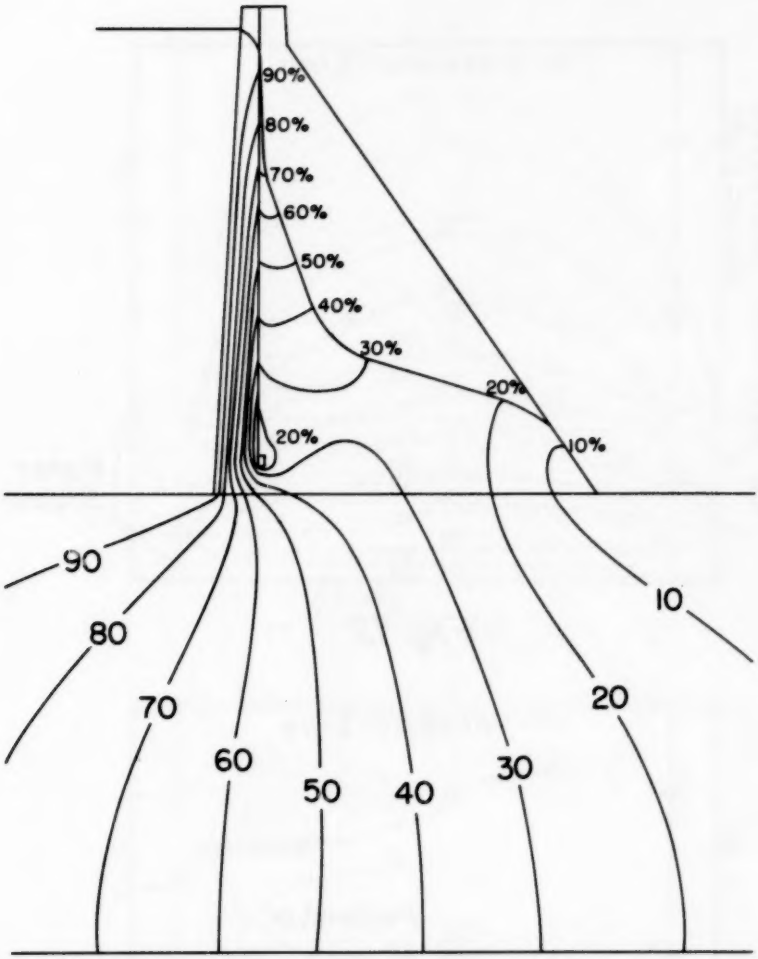

Fig. 11

Discussion of Tests

The prime purpose of this paper is to present the results of the tests so that an experienced dam designer may draw his own conclusions therefrom. However, there appear to be several conclusions which may be drawn, and which will be brought out here for the purpose of discussion.

Figure 3 shows ideal results in reduction of seepage forces in the foundation. In Figure 17 the result from Figure 3 is plotted against the results of some of the actual measurements on existing dams as presented by Kenneth B. Keener, M. ASCE.[6] The results plotted for specific dams are for straight

6. Uplift Pressures in Concrete Dams, Trans ASCE, Vol. 116, p. 1218, 1951.

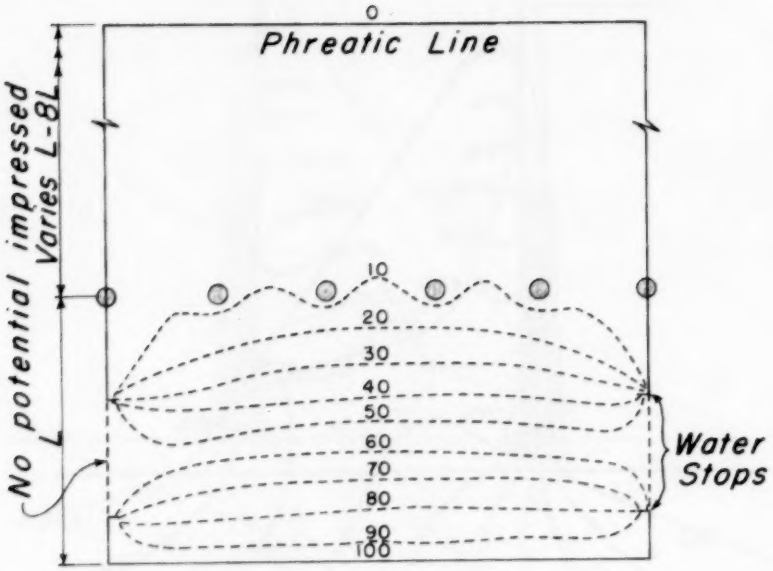
0
Phreatic Line
No potential impressed
Varies L-8L
L
10
20
30
40
50
60
70
80
90
100
Water
Stops

Fig. 12

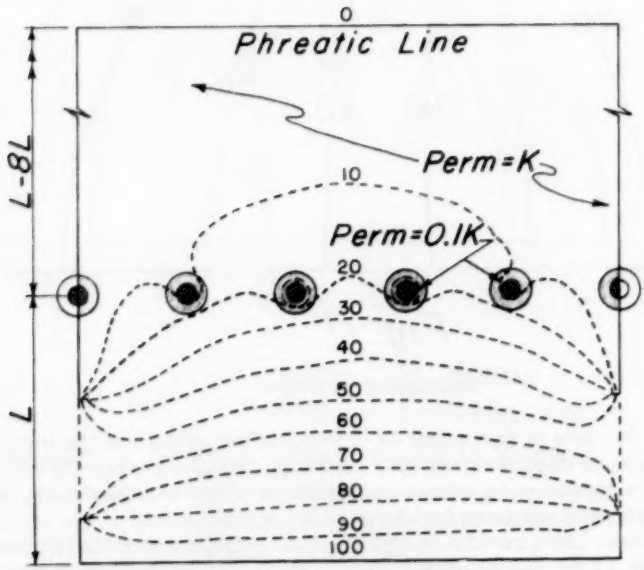
0
Phreatic Line
Perm=K
Perm=0.1K
L-8L
L
10
20
30
40
50
60
70
80
90
100

Fig. 13

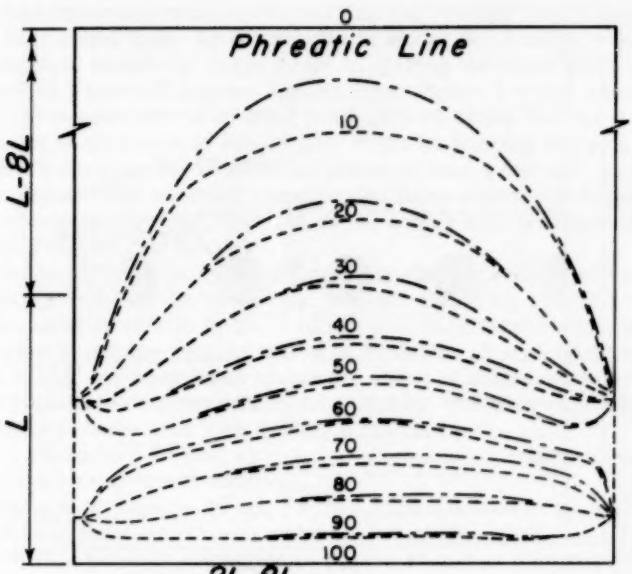
0
Phreatic Line
10
20
30
40
50
60
70
80
90
100
L-8L
L
2L-8L
L

Fig. 14

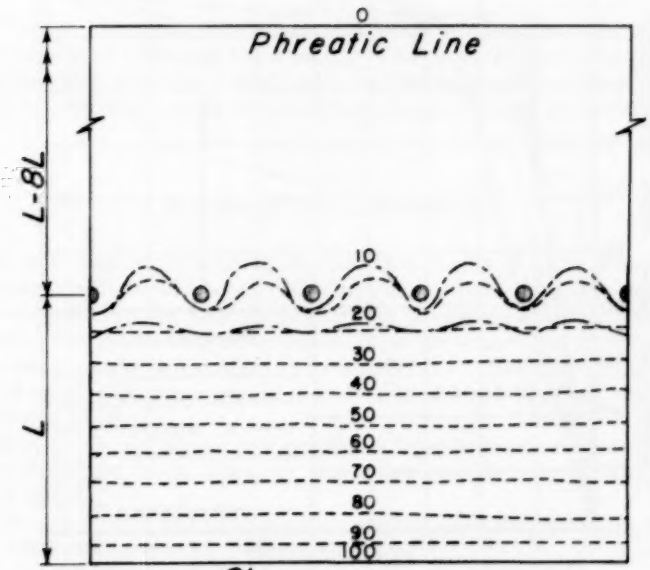
0
Phreatic Line
10
20
30
40
50
60
70
80
90
100
L-8L
L
8L
L

Fig. 15

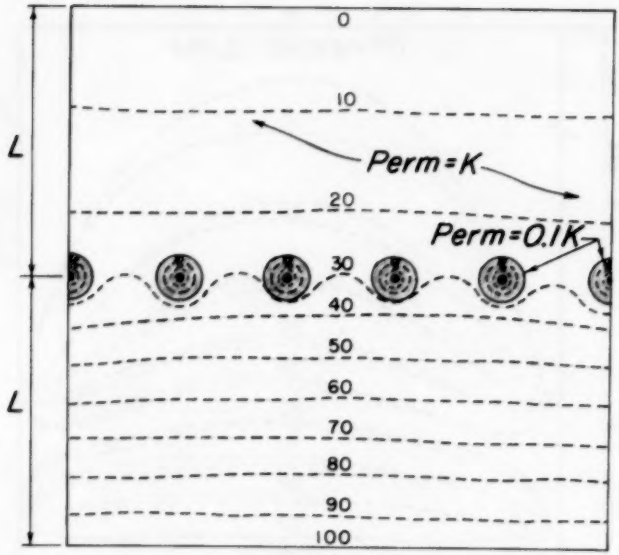
0
10
Perm=K
20
Perm=0.1K
30
40
50
60
70
80
90
100
L
L

Fig. 16

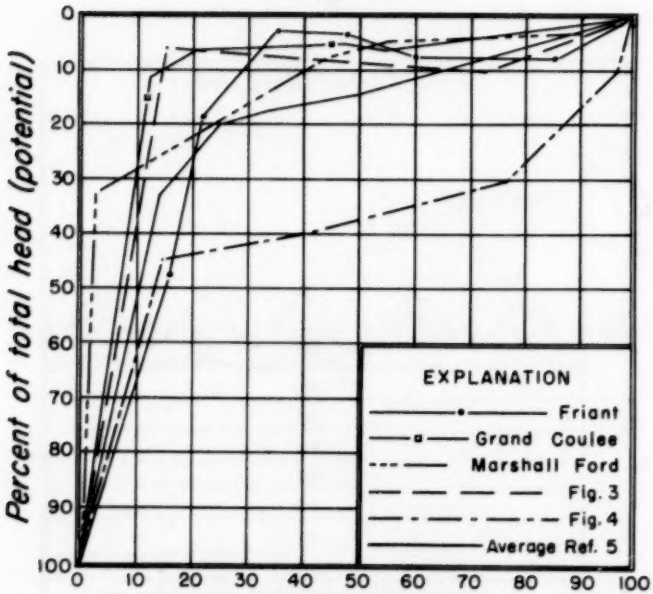
Percent of total head (potential)
0
10
20
30
40
50
60
70
80
90
100
0
10
20
30
40
50
60
70
80
90
100
EXPLANATION
Friant
Grand Coulee
Marshall Ford
Fig. 3
Fig. 4
Average Ref. 5
Distance in Percentage of base width

Fig. 17

gravity dams similar to the model. Assuming the correctness of measurement in the existing dams, this shows that these dams have obtained nearly the maximum reduction of pressure and that the average for all types of dams is not too high above this. As the results in Model No. 2 show, when compared to tests on Model No. 1, the error in making the drain solid is not great. Also plotted on Figure 17 are the results from Figure 4 which show that average reduction in pressure in existing dams is well below that for a cut-off only. Results of all the tests show that a drain functioning 100 per cent effectively is much more potent in reducing potential than a cut-off. However, the tests show that without a cut-off the potential lines around the drain are crowded very close together, thus indicating a very high flow into the drain with possible deleterious effects.

The principal feature in Figures 5 and 6 is that regardless of the ratio of permeability of concrete to foundation, whether 1:2; 1:10; or 1:00, the effect of this ratio upon potentials in the foundation is very small. Also the presence of drains in the concrete as shown in Model No. 2 would further reduce this small effect. As previously stated the effect of measures taken to reduce foundation potentials on potentials in the concrete was also very small, and would likewise be even less with drains in the concrete.

Figure 7 shows that as long as there is a reasonable imperviousness created by the cut-off it will function.

A comparison of Figures 10 and 11 with Figure 3 shows that the drains in the concrete are very effective in reducing potentials in the concrete. The effect on the foundation is negligible in Figure 10 and in Figure 11 there is a reduction from about 60 per cent to 40 per cent at the location of the foundation drain which is omitted. It should be pointed out that the permeability ratio is 1:1 and any increase in permeability ratio would decrease this reduction.

The effect of the drains in the concrete is clearly shown in Figures 12-16. These figures also illustrate the effect of open joints on relieving potentials. The figures which show the results with decreased permeability ($k = 0.1k_c$) for 4' around the drain, indicate that there is still a large reduction in pressure.

SUMMARY OF CONCLUSIONS

1. The most important conclusion from this series of tests is that measures taken to reduce foundation potentials have little effect on potentials in the concrete section, and vice versa, for any permeability ratio tested from 1:1 to 1:00. The problem of reducing uplift in the foundation is thus a separate, and very nearly independent, problem from the problem of uplift in concrete, if it exists. In some recent discussions of uplift this fact seems to have been lost sight of.

2. Both cut-offs and drains are desirable in reducing foundation uplift, with the major reduction due to drainage, but with a cut-off necessary to reduce volume of flows.

3. If the concrete is permeable and seepage forces exist, drains in the concrete section will greatly reduce potentials.

ACKNOWLEDGMENT

The model tests were performed by R.E. McLees, formerly Soils Mechanics Engineer, Sacramento District, who made many helpful suggestions.

TABLE 1

Model Series No.	Ratio of Permeabilities	Cutoff - Imperv. Drain - 7% Pot.	Cutoff - Imperv. Drain - 50% Pot.	Cutoff - Imperv. Gallery - 7% Pot.	Cutoff - Imperv. Drain - None	Cutoff k = ko Drain - 7% Pot.	Cutoff k = ko Drain - 50% Pot.	Cutoff k = ko Gallery - 7% Pot.	Cutoff k = ko Drain - None	Cutoff k = 5ko Drain - 7% Pot.	Cutoff k = 5ko Drain - 50% Pot.	Cutoff k = 5ko Gallery - 7% Pot.	Cutoff k = 5ko Drain - None	No Cutoff Drain - 7% Pot.	No Cutoff Drain - 50% Pot.	No Cutoff Gallery - 7% Pot.	No Cutoff No Drain	No. Models	Tailwater
A	1:10	1	2	3	4													4	0
B						1	2	3	4									4	0
C										1	2	3	4					4	0
D														1	2	3	4	4	0
E		1	2	3	4													4	.25H
F						1	2	3	4									4	0
G										1	2	3	4					4	0
H	1:10													1	2	3	4	4	.25H
I	1:00	1	2	3	4													3	0
J						1	2	3	4									3	0
K	1:00									1	2	3	4					2	.25H
L	1:2	1	2	3	4													3	0
M						1	2	3	4									2	0
N										1	2	3	4					3	0
O		1	2	3	4													4	0
P						1	2	3	4									3	.25H
Q	1:2									1	2	3	4					3	.25H
																		68	

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JULY: 457(AT), 458(AT), 459(AT)[c], 460(IR), 461(IR), 462(IR), 463(IR)[c], 464(PO), 465(PO)[c].

AUGUST: 466(HY), 467(HY), 468(ST), 469(ST), 470(ST), 471(SA), 472(SA), 473(SA), 474(SA), 475(SM), 476(SM), 477(SM), 478(SM)[c], 479(HY)[c], 480(ST)[c], 481(SA)[c], 482(HY), 483(HY).

SEPTEMBER: 484(ST), 485(ST), 486(ST), 487(CP)[c], 488(ST)[c], 489(HY), 490(HY), 491(HY)[c], 492(SA), 493(SA), 494(SA), 495(SA), 496(SA), 497(SA), 498(SA), 499(HW), 500(HW), 501(HW)[c], 502(WW), 503(WW), 504(WW)[c], 505(CO), 506(CO)[c], 507(CP), 508(CP), 509(CP), 510(CP), 511(CP).

OCTOBER: 512(SM), 513(SM), 514(SM), 515(SM), 516(SM), 517(PO), 518(SM)[c], 519(IR), 520(IR), 521(IR), 522(IR)[c], 523(AT)[c], 524(SU), 525(SU)[c], 526(EM), 527(EM), 528(EM), 529(EM), 530(EM)[c], 531(EM), 532(EM)[c], 533(PO).

NOVEMBER: 534(HY), 535(HY), 536(HY), 537(HY), 538(HY)[c], 539(ST), 540(ST), 541(ST), 542(ST), 543(ST), 544(ST), 545(SA), 546(SA), 547(SA), 548(SM), 549(SM), 550(SM), 551(SM), 552(SA), 553(SM)[c], 554(SA), 555(SA), 556(SA), 557(SA).

DECEMBER: 558(ST), 559(ST), 560(ST), 561(ST), 562(ST), 563(ST)[c], 564(HY), 565(HY), 566(HY), 567(HY), 568(HY)[c], 569(SM), 570(SM), 571(SM), 572(SM)[c], 573(SM)[c], 574(SU), 575(SU), 576(SU), 577(SU), 578(HY), 579(ST), 580(SU), 581(SU), 582(Index).

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FEBRUARY: 608(WW), 609(WW), 610(WW), 611(WW), 612(WW), 613(WW), 614(WW), 615(WW), 616(WW), 617(IR), 618(IR), 619(IR), 620(IR), 621(IR)[c], 622(IR), 623(IR), 624(HY)[c], 625(HY), 626(HY), 627(HY), 628(HY), 629(HY), 630(HY), 631(HY), 632(CO), 633(CO).

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APRIL: 659(ST), 660(ST), 661(ST)[c], 662(ST), 663(ST), 664(ST)[c], 665(HY)[c], 666(HY), 667(HY), 668(HY), 669(HY), 670(EM), 671(EM), 672(EM), 673(EM), 674(EM), 675(EM), 676(EM), 677(EM), 678(HY).

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JULY: 732(ST), 733(ST), 734(ST), 735(ST), 736(ST), 737(PO), 738(PO), 739(PO), 740(PO), 741(PO), 742(PO), 743(HY), 744(HY), 745(HY), 746(HY), 747(HY), 748(HY)[c], 749(SA), 750(SA), 751(SA), 752(SA)[c], 753(SM), 754(SM), 755(SM), 756(SM), 757(SM), 758(CO)[c], 759(SM)[c], 760(WW)[c].

c. Discussion of several papers, grouped by Divisions.

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